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A comprehensive study on decontamination of food-borne microorganisms by cold plasma

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ABSTRACT

Food-borne microorganisms are one of the biggest concern in food industry. Food-borne microorganisms such as *Listeria monocytogenes, Escherichia coli, Salmonella* spp., *Vibrio* spp., *Campylobacter jejuni, Hepatitis A* are commonly found in food products and can cause severe ailments in human beings. Hence, disinfection of food is performed before packaging is performed to sterilize food. Traditional methods for disinfection of microorganisms are based on chemical, thermal, radiological and physical principles. They are highly successful, but they are complex and require more time and energy to accomplish the procedure. Cold plasma is a new technique in the field of food processing. CP treatments has no or very low effect on physical, chemical and nutritional properties of food products. This paper reviews the effect of plasma processing on food products such as change in colour, texture, pH level, protein, carbohydrate, and vitamins. Cold plasma by being a versatile, effective, economical and environmentally friendly method provides unique advantages over commercial food processing technologies for disinfection of food.

1. Introduction

Over the last few years, people have grown skeptical about the health effects of processed food (Gavahian and Khaneghah, 2020; Zhu et al., 2020; Schneider et al., 2009). Therefore, the demand in market for healthy food has considerably increased (O'Beirne et al., 2014; Sagdic, Ozturk, and Tornuk, 2013). With the change in consumer demands and food safety guidelines, food processing technologies have changed as well. Ensuring good quality and safety of food has become a difficult task in recent years (Liao et al., 2020). Food surface is easily contaminated by pathogenic microorganisms of manure compost during the process of harvesting. Ready-to-eat products available in the market have been increase, which do not require heating (Bagheri, Abbaszadeh, and Salari, 2020), and with that various food borne diseases have also increase recently (Cui, Zhao, and Lin, 2015; Beuchat, 1996) (Fig. 1).

Cleaning and disinfection are crucial processes during food processing to ensure hygienic products and food safety. Different types of chemical and physical processes are used for disinfection of food to prevent pathogenic and harmful microorganisms (Cui et al., 2016). Commercial methods for the inactivation of microorganisms are based on chemical principles (Fernández et al., 2012). Non-thermal methods are preservation of food that are effective at sub-lethal temperatures, thus it minimize negative effects on nutritional value of food (Tiwari, O'Donnell, and Cullen, 2009). These include the application of gamma irradiation, beta irradiation (electron beam), UV treatment, power ultrasound, pulsed light, high hydrostatic pressure and pulsed electric field (PEF). They are effective but limited to certain types of food products and consume more energy and time. Purely physical procedures, such as high hydrostatic pressure, are chemically secure, but they necessitate complicated and costly equipment. (Rastogi et al., 2007), and this can affect the quality of food product (Kruk et al., 2011). Therefore, several food handling systems are being investigated for use on food packaging surfaces (Kowalonek, Kaczmarek, and Dbrowska, 2010). Cold plasma is a new approach that has drown the interest of food science and researchers (Basaran, Basaran-Akgul, and Oksuz, 2008; Selcuk, Oksuz, and Basaran, 2008; Vleugels et al., 2005).

The use of cold plasma to decontaminate fresh fruits and vegetables is a new technology (Pankaj et al., 2014). Plasma processing is a flexible method that can be used on a wide range of food items, including cereal, meat, poultry, dairy, fruits and vegetables, as well as packaging. (Critzer et al., 2007; Kim et al., 2017; Niemira and Sites, 2008). Cold plasma treatment can inactivate microorganisms on the surface of food products

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without increasing the temperature (Fernández et al., 2012). Cold plasma includes reactive species such as electrons, free radicals, positive and negative ions, UV photons, and excited or non-excited molecules and atoms, all of which can be used to sterilize food (Hoffmann, Berganza, and Zhang, 2013). Furthermore, the temperature of the plasma glow is low since these active species are not in thermodynamic equilibrium (<60 °C). As a result, it's known as cold plasma is classified as a non-thermal technology (Misra & Pankaj, 2014).

Chemical washing is done with antimicrobial compounds such as chlorine, hydrogen peroxide, ozone, and managed atmospheric storage are used during the processing of fruits and vegetables to minimize bacterial content (Mahajan et al., 2014). Fresh-cut vegetables are highly bacterial risky due to all operations such as peeling or chopping, dipping or shredding before wrapping (Rico et al., 2007). Thermal therapy is an alternative to microbial food reduction, but heat sensitive vegetables and fruits, which can cause improvement in fruit and vegetable quality attributes. Thus, in comparison to other non-thermal treatment such as ionizing radiations, high hydrostatic strain, pulsed energy champions, oscillating magnetic fields and high performance ultrasound, cold plasma technology offers the opportunity for industrial cost reductions (Tiwari, O'Donnell, and Cullen, 2009). In addition to microbial decontamination, it helps to amend the food content with the desired characteristic and preserves the nutritive and textural properties. Thus, in order to conduct decontamination, it is essential to consider the relationship of cold plasma with the surface of food materials.

Killing of microorganisms is the most essential element for the food safety. There are numerous microorganisms present on food surfaces. *Escherichia coli* is the most common food-borne microorganism found in most of the fruits and vegetables. *Listeria monocytogenes* is another microorganism for food security problem because it is prevalent in the environment (Ukuku et al. 2015). New strawberries, cut apples, and stone fruits such as whole peaches, nectarines, and plums have also been shown to contain *L. monocytogenes*, which can cause a variety of diseases. Plasma-activated atoms and ions induce molecular sandblasting, destroying organic and inorganic pollutants.

2. Comparison between cold plasma and other decontamination methods

There are many traditional methods for decontamination of food, such as thermal, chemical, radiation, etc (Ascp and Weber, 1999; Sureshkumar et al., 2010). Food-borne diseases are increased due contamination by viruses, pathogen, parasite, and other microorganism on fruits, vegetable, meat, dairy and fish products.

Thermal technique is one of the most ancient technique for food sterilization (Sureshkumar et al., 2010). Thermal pasteurization of liquid product such as milk are well established and satisfied approach. However, it is not guaranteed for solid product. Many food products are heat sensitive or it has some components which can show unwanted results. Thermal sterilization in medical facilities is not considered an ideal approach. Furthermore, thermal treatment has to be handled carefully or it can be harmful to the personnel. Food packaging can also be used to minimize contamination. If possible, the product could be preheated or pasteurized before packaging to minimize the infection. However, there is still a chance of getting infected by viruses by surface cross-contamination.

Chemical disinfectants are used for recent few centuries. It includes chlorine, alcohols, acids, alkalis, bleach etc (Filipi et al., 2020). Chemical disinfectants are one of the economical method, but it has only short-term effect. It is considered better for surface disinfection, but it can react with the components on food surface and make even more dangers components. Ethanol and Isopropanol are mostly used for surface disinfectants. Human body have many microorganism, which can be killed by chemical disinfectants, but ethanol and many other chemical could be toxic to human body (Moisan et al., 2013).

Antibiotics is one of the most frequently used disinfectants for bacteria. Different antibiotics are available for different bacteria and doses are established, which gives it a natural preference for decontamination. However, it is not considered fully safe for food decontamination. Decontamination from antibiotics can take a long time. Many bacteria can show resistance to antibiotics and can even survive in the presents of an antibodies. Furthermore, if it is applied on human body, it could show side-effect like skin infection, Nausea, Vomiting, Diarrhea, loss of appetite, stomach pain, etc (Mammadova et al., 2019).

Irradiation is one of the physical process, studied thoroughly from last few decades (Section, Atomic, and Agency n.d.). The irradiation processes using gamma, electron beam, infrared and microwave, but again radiation should be handled with precaution or it could be harmful. It can only be used to sterilized pre-packed food material. Hence, it can't be used directly on food surface, or it could show undesirable effects. Radiation treatment will sterilize the entire body. Thus, it can't be use for disinfection on a single spot. Radiation treatment should be handled with precaution or it could be harmful to the personnel. Furthermore, radiation sterilization is not cheap.

Alcohol is used in sanitizer, has shown good response for flu viruses. Ethyl alcohol is a powerful germicide that is considered better

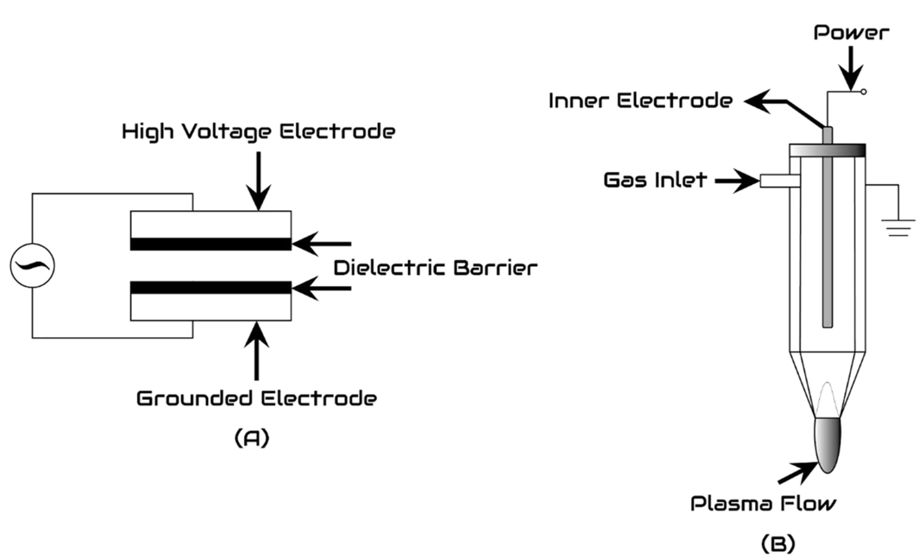

Fig. 1. (a) Schematic Diagram of DBD, (b) Schematic Diagram of Plasma Jet (Misra et al., 2016).

than isopropyl alcohol and other options. To be effective, any sanitization must contain at least 70% of alcohol solution (Wadhams, 1998). Alcohol sensitization does not show the desired results if the concentration of alcohol falls below 50%. Ethyl alcohol and isopropyl alcohol are two chemical substances that are widely utilized in hospitals. These alcohols are bactericidal and fungicidal (Rutala and Weber, 2013). However, if it is used very often as a disinfectant, alcohol can cause swelling, hardness, cracking, and even color loss. Since, alcohol is flammable it is not 100 % safe to be use as a surface decontamination. A 40-year health care worker, experienced hand burn after using alcohol gel sanitizer (O'Leary and Price, 2011). This case demonstrated the possible danger of using alcohol hand gel sanitization, specially for smokers or someone who is working in thermal associated facility.

Cold plasma does not produce radiation, chemical toxicity, high heat, or any other undesirable byproducts, thus considered environmentally friendly. Because it operates under Atmospheric Temperature and Pressure and it is simple to use (Chen et al., 2020; Misra & Patil, 2014; Park et al., 2008; Rossow, Ludewig, and Braun, 2018). It can be operated without vacuum (Sharma et al., 2018). Thermal, chemical and radiation sterilization can't be used in open, it needs controlled atmosphere. Organic or inorganic impurities are also decontaminated. The use of cold plasma has also been proven to reduce contaminants from the surface of industrial materials such as iron and steel (S. Y. Park and Ha, 2018). Thus, cold plasma can be used to decontaminate heavy metal particles like iron and steel (Ramaswamy et al., 2019). Decontamination of liquid products by cold plasma has shown sufficient log reduction form water, milk, fruits juices, etc (Aggelopoulos and Tsakiroglou, 2021). It is a pollution free technique for bacterial and viral disinfection (Bute et al., 2020). Cold plasma processing had no or little changes on nutritional value or any other physical characteristics. Other advantages of cold plasma therapy include reasonably good food composition preservation, low energy costs, and fast processing. There are many traditional methods that can be used for sterilization, but cold plasma being a versatile, effective, and environmentally friendly method provides unique advantages over commercial sterilization technologies.

3. Plasma physics and chemistry

Plasma is the fourth and final state of matter. It's a partly ionized gas made up of electron, photons, uncharged atoms and molecules, ozone and free radicals (Hoffmann, Berganza, and Zhang, 2013). The antimicrobial effect of this ionized gaseous mixture of active species. Plasma discharges are commonly used in manufacturing and are critical in a variety of technical applications (Milosavljević, Karkari, and Ellingboe, 2007). Cold plasma is operated in less than 60° C (Alves Filho, de Brito, and Rodrigues, 2019). Cold Plasma is an electrically conducting quasi-neutral 'sea' of electrons, ions, and reactive and neutral molecules (Claro et al., 2015). Adding gas mixtures can give different reactive atoms and molecules like reactive oxygen, UV photons and nitrogen molecules (Stoffels, Sakiyama, and Graves, 2008). For example, reacting oxygen and air can make large amount of atomic oxygen, superoxide, hydroxyl radicals, nitric oxide, hydrogen peroxide, and many more, which are all considered to kill the microorganism (Liu et al., 2010). Helium can reduce the cost of power requirement as it is easily ionized. However, atmospheric air is more economic since it is abundantly available in nature and less expensive than helium (Niemira, 2012).

Plasma chemistry is a complex science comprising a host of chemical reactions on various scales. Interaction of plasma with food surfaces is difficult to understand because it has numerous chemical reactions amongst 75 different species. The atmospheric plasma technique is effective in the breaking most organic bonds (i.e., C–H, C–C, C═C, C–O, and C–N) of surface contaminants. It helps in breaking contaminants with high molecular weight (Donegan, Milosavljević, & Dowling, 2013). The oxygen species produced in the plasma conduct a second purification action (O^{+}_2, O_2^{-}, O_3, O, O^+ and O^-, ionized ozone and free electrons). The radicals lead to the formation of H_2O, CO, CO_2 with organic contaminants. The reaction, which ultimately leads to OH production, implemented in the process of DBD are listed below (Foster et al., 2018).

$$O_3 + HO_2 \rightarrow HO_2 + O_3$$

$$HO_2 \leftrightarrow H^+ + O_2^-$$

$$O_3 + O_2^- \rightarrow O_2 + O_3$$

$$O_3^- + H^+ \rightarrow HO^3$$

$$HO^3 \rightarrow O^2 + OH$$

Cold plasma inactivates microorganisms through three main techniques. First is the chemical reaction of radicals, reactive species, or charged particles with cell membranes. Second is by UV radiation damage to membranes and interior cellular components. Finally, UV produced during plasma species recombination may cause DNA strands to break. However, greatest results are seen by combination of multiple antimicrobial mechanism (Laroussi, 2002; Moisan et al., 2002). Free ions and electrons of plasma are produced by electrode using radiofrequency (RF), microwave (MW), or dielectric barrier discharge (DBD). In other cases, different types of method is used to generate plasma like; Uniform glow discharge plasma (Critzer et al., 2007), Corona Discharge Plasma Jet (Santos et al., 2018), Atmospheric cold plasma (Shi et al., 2017) and many more.

Dielectric barrier discharge is one of the easiest method to producing cold plasma. DBD has a huge anti-microbial potential to kill the contaminants present on the food and increase the shelf life without compromising the food safety or the nutritional value (Feizollahi, Misra, and Roopesh, 2020). DBD is generated by the electrical discharge between two electrodes, normally constructed with copper, which is separated by an insulating dielectric barrier (O'Connor, Milosavljevi, and Daniels, 2011). During this process argon, helium or any other noble gas (because they are inert in nature) enclosed within the glass walls act as a dielectric barrier to form cold plasma (Misra et al., 2011).

A sinusoidal voltage is applied to one of the dielectric plates and the other plate is electrically grounded. When high-voltage alternating current is supplied, the electron from the atom are separated forcefully from the atom forming ions and free electrons. This will result in an exponential growth in the number of electrons. This flow of electrons is cold plasma. Glass, quartz, ceramics, and polymers are all popular dielectric materials (Liang et al., 2011). The plasma formed does not react with large particles. However, small entities such as microorganisms or viruses can be eliminated (Moreau, Orange, and Feuilloley, 2008). It also reacts with different compounds to form OH^- radicals which can be easily separated. This make cold plasma very unique for the decontamination of bacteria, viruses, pathogen or any other types of microorganism. The DBD is considered one of the most energy efficient and economic plasma generator among the various forms of Plasma Generators.

4. Effect of cold plasma on food

4.1. Vegetables

Demand for fresh and natural food is increased in the market resent years. As a basic preservation strategy to assure quality of stored food, atmospheric packaging in addition with refrigeration is increasingly being used. However, because of the use of numerous gases in packaging and refrigeration process, the freshness of many food products is decreasing, and many food-borne diseases are spread between their consumers (Francis, Thomas, and O'Beirne, 1999). Newly harvested vegetables and fruits are mainly decontaminated with chlorine solution. Chlorine traces in food products are done by chemicals that are harmful to humans (Allende et al., 2008; Rico et al., 2007). Organic and inorganic contamination can lead to health risk (X. Chen and Hung, 2017;

Luo et al., 2018). Methodologies for inactivation of microorganisms, pathogens, viruses with preserving the nutritional value are currently under evaluation (Cossu et al., 2018; Goodburn and Wallace, 2013; Guo, Huang, and Chen, 2017; Marti, Ferrary-Américo, and Barardi, 2017; Thorn, Pendred, and Reynolds, 2017). Incidents regarding food safety have been increased in recent years due to the increase in use of pesticides and other chemicals (Beuchat, 2002). Every year, bacterial contamination causes 34% of all worldwide food safety problems (Frieden, 2010). *E. coli O157:H7, L. monocytogenes, Salmonella typhimurium KCTC 1925* are one of the most commonly found food-borne microorganisms. *E. coli O157:H7* is found on most of the food surfaces, responsible for majority of foodborne disease. Bovine gastrointestinal track is believed to be the main reservoir of *E. coli O157:H7*. Gastroenteritis and hemorrhagic colitis are one of the major symptoms caused by *E. coli O157:H7* (Yamada et al., 1993). Thus, food products associated with faeces are considered to be at risk of being contaminated *by E. coli. O157:H7. L. monocytogenes* is considered present nearly everywhere in the environment (Francis, Thomas, and O'Beirne, 1999). It is rod-shaped Gram-positive bacteria that can cause disease like Meningitis, Septicemia and it can even cause miscarriages (Höhn and Nell, 2015; Pourkaveh et al., 2016; Wing and Gregory, 2002). *Salmonella* is one of the gram-negative rod shaped bacteria. It is faecal associated microorganism thus it can contaminate food if sewage water or contaminated water is used for agriculture. Diarrhea, Nausea, Abdominal pain, Vomiting, fever, etc are the symptoms caused by *Salmonella* microorganism (Gordon, 2008; Kunwar et al., 2013). The types of microorganisms and their disinfection conditions are listed in the Table 1. Vegetables were studied under cold plasma to inactivate *L. monocytogenes* and *E. coli O157:H7* in the studies (mentioned in the table below) related to microorganism inactivation. A DBD plasma device was used within a frequency range of 15–60 Hz and a voltage supply of 60 kV is required to eliminate the E. coli ATCC 25922 type of microorganisms (Misra & Pankaj, 2014; Prasad et al., 2017). However, *Salmonella* spp. can be eliminated easily at a lower frequency (7 kHz) and voltage (10 kV) (Critzer et al., 2007).

4.2. Fruits

Fruits, similar to vegetables, they may be infected with pathogenic microorganisms from livestock and manure compost during the irrigation, harvesting, and transportation processes. Traditional postharvest washing and sanitizing methods for food are insufficient. Microbial reductions of less than 2 log units are shown very often by conventional methods in comparison to cold plasma (Niemira, 2012). Research has shown that harmful bacteria may grow on a large scale for fresh and fresh-cut fruit surfaces (Microbiology, 2005). Cold plasma process can promise decontamination of microorganisms and quality enhancement of fruits (Mir et al., 2020). Cold plasma has shown significant reduction in surviving microorganism like *E. coli O157:H7* and *Salmonella* Stanley on surface of Golden Apple (Niemira and Sites, 2008). Inactivation of Salmonella was time dependent, with each increasingly longer treatment giving considerable incremental increases in pathogen inactivation (Niemira and Sites, 2008). In fruits, water content is high, thus most of the fruits are heat sensitive. Due to this surface structure or color may change after thermal treatment. Increment in Color and Vitamin-C content has been seen after cold plasma treatment (Ramazzina et al., 2015). *Saccharomyces cerevisiae* is one of the persistent microorganism mostly found on Melon and Mango, shown significant reduction in 10 s on mango and 30 s on melon after plasma processing (Perni et al., 2008).

Fresh cut fruits have to be treated in different conditions because the micro-organisms present inside and outside the fruit can be different (Bagheri and Abbaszadeh, 2020). The types of microorganisms that can be eliminated at different processing conditions are listed in the Table 2. In the studies (mentioned in the table below) related to inactivation of microorganisms show fruits processed under cold plasma to decontamination. The fruits have different shapes and they come from different parts of the world. Therefore, they have different micro-organisms. Hence, the processing conditions are different. Several kinds of apples are tested in studies and it is shown that the microorganisms on the surface of the apples can be killed by processing it for 2–5 min. The

Table 1
Processing condition for inactivation of microorganisms present on surface of vegetables by cold plasma.

Food Product	Type of Plasma	Processing Condition	Microorganisms	Changes	References
Cabbage	Microwave-powered cold plasma	400–900 W, 667 k Pa, 1–10 min	*L. monocytogenes*	No change	(Lee et al., 2015)
Cucumbers and Carrots and Pears	Plasma jet	500 V, 30 mA, 1–8 min	*Salmonella*	Decrease in colour, moisture and vitamin-c	(Wang et al., 2012)
Lettuce	ICDPJ	2.4 kHz, 34.8kv, 5 min	*A. hydrophila*	No change	(Min et al., 2017)
Lamb's lettuce	Plasma jet	35 W, 7.12 MHz, 40 s	*NA*	Decrease in acidity	(Grzegorzewski et al., 2011)
Romaine lettuce	DBD	42.6 kV, 10 min	*Escherichia coli O157:H7*	No change	(Min et al., 2017)
Red chicory	DBD	19.15 V, 3.15 A, 15 min	*L. monocytogenes*	No change	(Trevisani et al., 2017)
Iceberg Lettuce	OAUGDP	9 kV, 6 kHz, 25 °C, 3–5 min	*L. monocytogenes*	No change	(Critzer et al., 2007)
Cherry Tomatoes	DBD	100 kV, 150 s	*E.coli, listeria innocua*	No change	(Ziuzina et al., 2016)
Tomato	DBD	15 Hz and 60 kV, from 5 to 30 min	*E. coli ATCC 25,922*	No change	(Prasad et al., 2017)
Radish	Microwave- powered plasma	900 W, 667 Pa, 10 min	*S. typhimurium*	Decrease in the moisture content	(Oh, Young Song, & Min, 2017)
Corn	HVACP	90 kV, 50 Hz, 10 min	*Aflatoxins*	No change	(Shi et al., 2017)
Zain	DBD	75 V, 10 min	*NA*	tensile strength increased	(Dong et al., 2017)
Spinach	DBD	50 Hz, 12Kv, 5 min	*E. coli ATCC 25,922*	No change	(Klockow and Keener, 2009)
Pumpkin	ICDPJ	17 kV, 20 min	*E. coli ATCC 25,922*	Decrease in pH	(Santos et al., 2018)
Onion powder	Microwave plasma	400–900 W, 2.45 GHz, 0.7 kPa, 1 L/min, 10–40 min	*A. brasiliensis, E. coli O157:H7*	No change	(Kim et al., 2017)

(DBD) - Dielectric barrier discharge.
(OAUGDP) - One Atmosphere Uniform Glow.
(HVACP) - High voltage atmospheric cold plasma.

Table 2
Processing condition for inactivation of microorganisms present on surface of fruits by cold plasma.

Food Product	Type of Plasma	Processing Condition	Microorganisms	Changes	References
Apple	DBD	150 W, 12.7 kHz, air, 120 min	*E. coli O157:H7*	Reduction of antioxidant	(Ramazzina et al., 2016)
Golden apple	GACP	15 kV, 60 Hz, 3 min	*Salmonella Stanley and E. coli O157: H7*	No change	(Niemira and Sites, 2008)
Granny smith apples	Plasma jet	40 Hz, 36 kV, 5 min	*L. monocytogenes*	Changes in apple surface structure	(Ukuku, Niemira, and Ukanalis, 2019)
Melon	DBD	12.5 kHz, 15 kV, 30 min	*NA*	reduction in peroxidase	(Tappi et al., 2016)
Banana starch	Corona electrical Discharge plasma	50 kV/cm, 3 min	*NA*	Pasting temperatures rise when peak viscosity falls	(Wu, Sun, and Chau, 2018)
Cantaloupe	OAUGDP	9 kV, 6 kHz, 25 °C, 1 min	*Salmonella* spp.	No change	(Critzer et al., 2007)
Mandarins	Microwave- powered cold plasma	2.45 Hz, 0.7 k Pa, 900 W, 10 min	*P. italicum*	Peel has more overall phenolic and antioxidants	(Won, Lee, and Min, 2017)
Mangoes and melons	Cold atmospheric plasma	12–16 kV, 30 kHz, 1 min	*Pantoea agglomerans, E. coli, Saccharomyces cerevisiae, Gluconacetobacter liquefaciens*	No change	(Perni et al., 2008)
Kiwi	DBD	15 kV, 10–20 min	*NA*	Colour enhancement, improved vitamin-C, and acidity	(Ramazzina et al., 2015)
Strawberries	DBD	50 Hz, 60 kV, 5 min	*Aerobic bacteria and yeasts and moulds*	No change	(Misra & Patil, 2014)
Blueberry	DBD	80 kV, 60 Hz, 5 min	*NA*	Acidity and colour change	(Sarangapani, O'Toole, Cullen, & Bourke, 2017)
Unpeeled almond	Diffuse coplanar surface barrier discharge	20 kV, 15 kHz, 15 min	*Salmonella*	Colour change	(Hertwig et al., 2017)
Almond slices	DBD	3.95–12.83 kV, 10 min	*NA*	No change	(Shirani, Shahidi, and Mortazavi, 2020)
Groundnuts	Radiofrequency plasma	60 W, 13.56 MHz	*Aspergillus parasiticus, Aspergillus flavus*	No change	(Devi et al., 2017)

(DBD) - Dielectric barrier discharge.
(GACP) - Gliding arc cold plasma.

processing condition for normal apple is at a lower frequency (5–10 kHz) and voltage (10 kV) and (Critzer et al., 2007) for decontamination of *E. coli*. *Salmonella* is mainly found on the surface of almonds. It took 15 min at a frequency and voltage of 15 kHz and 20 kV, respectively, (Hertwig et al., 2017) for decontamination of Salmonella. Increases in humidity in environment near dried fruits during storage and distribution can result in increased water activity, compromising microbiological quality and safety (Moraga et al., 2011).

4.3. Grains

Grains are produced in large quantity and stored in Godown for later sell and use. While storage grains could be invade by 25 distinct species of fungi (DUAN et al., 2007). *Penicillum* are one of the most commonly found microorganisms that are responsible for spoilage of food storage. They produce changes in order, color and reduction in nutritional value (Selcuk, Oksuz, and Basaran, 2008) (Table 3).

Decontamination of grains is hard to perform because of their small size (Gupta et al., 2020). In all these studies (mentioned in the table below) related to inactivation of microorganisms show grains tested

Table 3
Processing condition for inactivation of microorganisms present on surface of grains by cold plasma.

Food Product	Type of Plasma	Processing Condition	Microorganisms	Changes	References
Grains: wheat, chick pea, bean, barley, oat, soy bean, lentil, corn, rye,	APP	20 kV, 300 W, 1 kHz, 5–20 min	*Aspergillus* spp., *Penicillin* spp.	Moisture Changed	(Selcuk, Oksuz, and Basaran, 2008)
Refined Wheat flour	DBD	50 Hz, 1–2.5 kV, 1–5 min	*Tribolium castaneum*	No change	(Mahendran et al., 2016)
Wheat flour	DBD	60–70 kV, 5–10 min	*Penicillin* spp.	No change	(Misra et al., 2015)
Rice starch	RFP	40–60 W, 13.56 MHz, 0.15 mbar, air, 5–10 min	*Penicillin* spp.	No change	(Thirumdas et al., 2017)
Black gram	RFP	13.56 MHz, 30–50 W, 5–15 min	NA	Reduction of hardness, preparation time, ash and humidity	(Devi, et al., 2017)
Brown Rice	RFP	40–50 W, 13.56 MHz, 5–10 min	*Bacillus cereus*	Reduction of cooking time, durability, chewiness and humidity	(Thirumdas et al., 2016)
Black paper corns	DBD	9.7–10.6 kV, 15 kHz, 20 min	NA	No change	(Bang et al., 2020)
Brown Rice	DBD	250 W, 15 kHz, 5–20 min	*E. coli O157:H7, Bacillus subtilis, Bacillus cereus*	Reduction in hardness and pH	(Lee et al., 2016)

(APP) – Atmospheric plasma jet.
(RFP) – Radio frequency plasma.

under cold plasma to inactivate *Penicillium spp*. For the decontamination of microorganisms of grains DBD and RF are commonly used. The most commonly found microorganism in grains is *Penicillium* spp. The results show that it took more time to decontaminate and kill the microorganisms present in the grains compared with that of vegetables and fruits (Mahendran et al., 2016). It took about 20 min for each bag of grains. However, the processing condition is comparatively less because of the small size. Grains required a frequency and voltage of 1 kHz and 20 kV, respectively (Selcuk, Oksuz, and Basaran, 2008) for the decontamination of *Penicillium* spp. However, study results of flour have shown even lesser input power. It took only 5–10 min and a frequency and voltage of 50 Hz and 2 kV, respectively (Mahendran et al., 2016) for the decontamination of microorganisms like *Penicillium*. Another type of microorganism is *Bacillus cereus* which is mainly found in brown rice. Brown rice is the most easily and heavily contaminated food present in the market. It took 13.56 MHz of frequency (Lee et al., 2016) for the decontamination of *Bacillus cereus*. These microorganisms influence - characteristics of food like color, flavor, and composition, which has an impact on the cooking and eating quality. *Bacillus subtilis* contamination of rice-based food items has been linked to food-borne illnesses in humans (Fangio, Roura, and Fritz, 2010). There are many non-thermal processes, such as chemical treatment, ultraviolet, ionizing radiation, and high pressure processing that can be used for decontamination. However, these methods have a few disadvantages, such as high application costs, the need for specialized equipment, the creation of unwanted residues, longer processing times and poorer efficiency (Yun et al., 2010). Black gram is one of the most consumed food products in India that contains protein, starch, dietary fibers, sugars and micronutrients such as vitamins, minerals, proactive phytochemicals and oil (Singh et al., 2004). However, nutritional value can be reduced due to components present in black gram like tannins and phytic acid, which reducing protein digestion and decreasing mineral bioavailability (Duhan et al., 1989).

4.4. Animal product

Salmonella enteritidis is a commonly found microorganism in eggs and chicken meat (Wan et al., 2017). A DBD cold plasma jet device are used at a frequency of 2–10 Hz and a voltage supply of approximately 30 kV is sufficient to eliminate *Salmonella enteritidis* type of microorganisms (Dirks et al., 2012; Lee et al., 2011). Chicken skin can be disinfected quickly because it commonly contains *Campylobacter jejuni* which can be killed easily in 1 min at a frequency and voltage of 1 MHz and 3 kV respectively (Rossow, Ludewig, and Braun, 2018). However, chicken thigh, requires more time and power than that of chicken skin (2–3 min) for decontamination (Moutiq et al., 2020). For egg shells, conventional disinfection methodologies are inefficient in removal the existence of Salmonella (Cui et al., 2016; Cui, Ma, and Lin, 2016). Egg shells usually consist *serovar Typhimurium*. Eggs have one of the highest numbers of microorganisms. Therefore, egg shell consumes more time and energy for decontamination than that of vegetables, fruits, grains and chicken thigh or skin. It has to be treated for 15–20 min at a frequency and voltage of 60 Hz and 30–85 kV respectively for the decontamination of *serovar Typhimurium*.

Atmospheric temperature plasma can also be used food packaging for prevention of secondary pollution (Deng et al., 2020). Secondary pollution is rampant in animal products. The pork is studied under two conditions: fresh pork and frozen pork, and both show change in color. Fresh pork took 3 min at a frequency and voltage of 2.45 GHz and 1.2 kV, respectively (Fröhling et al., 2012) for decontamination of *E. coli* by microwave-powered plasma. While frozen pork took 2 min at a frequency and voltage of 58 kHz and 20 kV, respectively (Choi, Puligundla, and Mok, 2016) for the decontamination of *L. monocytogenes* by corona discharge plasma. Pulsed discharge plasma is used to decontaminate of *Psychrobacter glacincola* from salmon at a frequency and voltage of 16 kHz and 11 kV, respectively, for 1 min (Zhang et al., 2019). A few types of microorganisms such as *Psychrobacter glacincola, Brochothrix thermosphacta, Pseudomonas fragi* are mainly found in sea food. Sea food the most heavily contaminated food presents in the market. Decontamination of fish is not arduous; it takes significantly less time for decontamination under the same processing condition. It took 1 min at a frequency and voltage of 16 kHz and 11 kV, respectively, for the decontamination of *Psychrobacter glacincola, Brochothrix thermosphacta, Pseudomonas fragi* (Zhang et al., 2019).

4.5. Seeds

The process of seed decontamination is done for reducing microorganism that infest the seed surface and tissue or to attack early seedling. A fine seed treatment should be safe for the seed, last for a long time before planting, and tolerate the treatment without leaving hazardous or undesirable residues (Spadaro and Gullino, 2005). Seed sterilization methods include bleach, ethylene oxide, fungicides hot water, aerated steam, etc. All of these techniques can result in a considerable decrease in seed germination. Cold plasma performs at low temperatures, it can decontaminate complex surface structures, it has no chemical toxicity, quick processing time and uniform treatment without destroying seeds (Dhayal, Lee, and Park, 2006). Plasma therapy enhanced plant growth, encouraged normal and healthy physiological performance, and increased plant yield. The utilization of this technique to sterilize seeds before planting might reduce the usage of agrochemicals throughout the crop cycle (Pérez-Pizá et al., 2019). Cold plasma can be used to alter the genes at the transcriptional level through which plant mutation and seed priming can be improved (Iranbakhsh et al., 2020). Cold plasma can be used to adjust wettability of plants. This can increase seed germination as germination is dependent on the effect of plasma on seed surface and water absorption (Bormashenko et al., 2015) (Table 4).

Cold plasma has been shown to be safe for use in germination enhancement, production rate, plant growth and other quality of seeds (Pérez-Pizá et al., 2019). It has been observed that seeds require less time for plasma processing compared with that of whole fruits and vegetables. Plasma flow rate and power requirement for the processing condition is also less. Atmospheric plasma can perform decontamination without damaging the DNA (Shapira, Bormashenko, and Drori, 2019). *E. coli, Alternaria Brassicicola, Solanum lycopersicum* are one of the most common contamination observed on the surface of seeds. Seeds were selected randomly and processed with a slight modification in the conditions to obtain the favorable condition. To avoid direct contact, seeds are inserted between the two electrodes coated with a 2 mm glass dielectric, then the current is applied at different voltage and frequency under the process condition (Varilla, Marcone, and Annor, 2020) as given in the Table 5.

4.6. Liquids products

Sterilization and pasteurization is used conventionally to ensure microbial safety in liquid product (Ozen and Singh, 2020). These process have shown good results, but they could cause quality reduction (Gonzalez and Barrett, 2010). Thermal processing can produce a variety of physical and chemical changes and can reduce nutritional bioavailability (Petruzzi et al., 2017). Non-thermal processing like cold plasma can be used to preserve nutritional and physical properties. Color change in food is an important factor for consumers' preference. Chemical reactions are responsible for the original color appearance of food, thus any change in color indicates the impact of processing conditions (Barba, Esteve, and Frígola, 2012). Industry uses this factor for quality control since it is the first thing that appears to show a change in nutritional value during food processing. Plasma treatment had no or minor effect on the color of the apple, orange, grape and pomegranate juices (Almeida et al., 2015; Kovačević, Danijela, & Kljusurić, 2016; Liao et al., 2018; Wang et al., 2018; Pankaj et al., 2017) (Table 6).

The contaminants on the surface of solid food products can be

Table 4
Processing condition for inactivation of microorganisms present on surface of Animal product by cold plasma.

Food Product	Type of Plasma	Processing Condition	Microorganisms	Changes	References
Chicken skin	Cold plasma jet	30–180 s, 1 MHz, 2–3 kV, 2 min	*Campylobacter jejuni*	No change	(Rossow, Ludewig, and Braun, 2018)
Chicken thigh	Pulsed gas plasma discharge	30 kV, 0.5 kHz, 0.15 W/ cm2, 2 min	*Salmonella enterica* subsp. *enterica serovar Typhi ATCC 19214, C. jejuni RM1849, L. innocua*	No change	(Ramazzina et al., 2015)
Egg shells	HVACP	85 kV, 60 Hz, 5 to 15 min	*Salmonella enteritidis, Salmonella enterica serovar Typhimurium*	No change	(Wan et al., 2017)
Egg shells	Cold nitrogen plasma	400 W, 20 min	*Salmonella enteritidis and Salmonella typhimurium*	Shelf life increased up to 14 days	(Cui et al., 2016)
Fresh Pork	Microwave-powered plasma	2.45 GHz, 1.2 kW, 3 min	*E. coli O157:H7*	Little change in colour	(Fröhling et al., 2012)
Frozen pork	CDP	20 kV, 58 kHz, 2 min	*L. monocytogenes*	change in colour	(Choi, Puligundla, and Mok, 2016)
Pork Loin	DBD	3 kV, 30 kHz, 5–10 min	*L. monocytogenes*	Decrease in pH	(Kim et al., 2013)
Lamb meat	DBD	80 kV, 50 Hz, 5 min	*Brochothrix thermosphacta*	No change	(Patange et al., 2017)
Beef jerky	RF plasma	200 W, 0–10 min	*Staphylococcus aureus*	No change	(Kim et al., 2014)
beef loin	DBD	9 kHz, 29.9 W	*Staphylococcus aureus, Listeria monocytogenes, Escherichia coli*	No change	(Bauer et al., 2017)
Ground pork	Plasma jet	7 kV, 25 kHz, 600 W, 60 min	NA	No change	(Lee et al., 2018)
Ham	CAP	13.56 MHz 150 W, 2 min	*L. monocytogenes*	No change	(Song et al., 2009)
Bacon	DBD	13.56 MHz, 125 W, 1.5 min	*L.monocytogenes KCTC3596, E. coli KCTC1682, Salmonella typhimurium KCTC 1925*	Shelf life increase	(Kim et al., 2011)
Bresaola	Atmospheric temperature plasma	15–62 W, 1 min	*L. innocua*	Colour change, Reduction of redness	(Rød et al., 2012)
Salmon	Pulsed discharge plasma	16 KHz, 11 kV, 1 min	*Brochothrix thermosphacta, Pseudomonas fragi, Psychrobacter glacincola*	No change	(Zhang et al., 2019)
Dried squid shreds	Corona discharge	58 kHz, 20 kV, 3 min	*Aerobic bacteria, Staphylococcus, marine bacteria*	No change	(Choi, Puligundla, and Mok, 2017)

Table 5
Processing condition for inactivation of microorganisms present on surface of Seeds by cold plasma.

Food Product	Type of Plasma	Processing Condition	Microorganisms	Changes	References
Cuman seeds	DBD	50 Hz, 2 kV, 59 mA, 3 min	NA	Seed germination enhanced	(Shashikanthalu, Sharanyakanth, & Radhakrishnan, 2020)
Mung bean seeds	NA	5 kV, 10 kHz, 20 min	*E. coli*	Reduction in E.coli	(Darmanin et al., 2020)
Soybean seeds	DBD	25 kV, 50 Hz, 3 min	NA	Production rate increase	(Pérez-Pizá et al., 2019)
Hemp seeds	DBD	8 kV, 13 kHz,80 W	NA	Improved plant early growth	(Iranbakhsh et al., 2020)
Radish seeds	Corona discharge plasma	7 kV, 1 Hz, 15 min	*Alternaria Brassicicola*	Surface wettability and germination increase	(Thammaniphit et al., 2020)
Pea seeds	DBD	35 W, 10 min	NA	Seedling growth improvement	(Gao et al., 2019)
Pumpkin seeds	Cold plasma jet	8 kV, 6 kHz,27 min	NA	Germination accelerated, seed growth increase	(Volkov et al., 2019)
Tomato seeds	Cold plasma jet	83 kV,0.63 kV 77 mA, 10 min	*Solanum lycopersicum*	NA	(Adhikari et al., 2020)

inactivated easily. However, for food products in liquid form, the plasma has to be dipped inside the liquid to ensure thorough contact of cold plasma with the microorganisms. Since cold plasma is dipped inside the solution, the setup of the decontamination of liquid becomes complex. Essentially, it is similar to creating a lightning inside the water or any other liquid. Therefore, decontamination of solid surfaces is easier to execute (Kim et al., 2014). Cold plasma has also shown enhancement of the protein present in milk (Sharma & Singh, 2020). Recently, numerous studies have taken place by improving the geometry. However, large scale disinfection of liquid requires further research (Foster et al., 2018).

5. Changes in food products after cold plasma

5.1. Nutritional value

Sterilizing and maintaining the true nutritional value of food have been a significant source of concern for the food industry. A disinfection technology’s goal is not only decontamination pathogen, but also shelf-life extension while preserving nutritional quality of food. In last decade, people have grown skeptical about the nutritional value of food available in the market (O’Beirne et al., 2014; Sagdic, Ozturk, & Tornuk, 2013). For food industries. cold plasma is a novel technology and a method to perform decontamination to obtain sterilized food without changing the nutritional value.

Vitamins are significantly sensitive and crucial substance for a healthy body. Therefore, it is essential to prevent a change in the vitamin value of the plasma processed food. Cold plasma is a technique which can fulfill that demand for the food industries. Many of previous work focuses on the impact of cold plasma on vitamin C. During plasma therapy with orange juice, a drop in vitamin is detected (Xu et al., 2017) as mentioned in Table 5. Riboflavin (B2), pyridoxine (B6), and biotin are some vitamins that are found stable. In this case, processing condition of

Table 6
Processing condition for inactivation of microorganisms present on surface of Liquid product by cold plasma.

Food Product	Type of Plasma	Processing Condition	Microorganisms	Changes	References
Water	Plasma jet	10 HZ, 25 kV	All the bacteria, viruses, chlorine compound and microorganisms	No change	(Foster et al., 2018)
Distilled water	DBD	60 Hz, 186 W, 1 min	*Salmonella enterica serovar Typhimurium LT2*	Decrease in ph.	(Mahnot et al., 2019)
Milk	DBD	15 kHz, 250 kV 5 min	*E. coli ATCC 25,922*	Decrease in ph.	(Kim et al., 2015)
Coconut water	DBD	60 Hz, 186 W, 2 min	*Salmonella enterica serovar Typhimurium LT2*	Decrease in ph.	(Mahnot et al., 2019)
Orange juice	HVACP	25 mL, 60 Hz,90 kV, 2 min	*Salmonella enterica serovar Typhimurium*	Decrease in ph., vitamin and colour	(Xu et al., 2017)
Apple juice	DBD	30–50 W, 1 min	*E. coli*	Change in colour, toxicity, and ph.	(Liao et al., 2018)
Apple juice	GPSDP	21.3 kV, 50 Hz, 30 min	*Zygosaccharomyces rouxii LB and 1130*	Change in colour, toxicity, and ph.	(Wang et al., 2018)
Blueberry juice	AJP	11 kV, 1000 Hz, 50 L/min, 6 min	*Bacillus* sp.	No changes	(Hou et al., 2019)
Grape juice	HVACP	80 kV, 60 Hz, 4 min	*Saccharomyces cerevisiae*	Change in pH	(Pankaj et al., 2017)
Pomegranate juice	Plasma jet	25 kHz, 3–7 min	NA	No change	(Kovačević & Danijela, 2016)

(AJP) - Atmospheric jet plasma.
(HVACP) - High Voltage Atmospheric Cold Plasma.
(GPSDP) - Gas Phase Surface Discharge Plasma.

cold plasma can be increased to its limits because the stable vitamins will not be affected during the process. There are a few unstable vitamins such as vitamin – A, C & E and Thiamin (B1) which can be easily altered (Dionísio, Gomes, and Oetterer, 2009). Therefore, it is essential to maintain the processing condition at minimum to ensure that nutritional quality of the food product remains unchanged.

Proteins helps to build muscles in the body which makes it necessary to maintain the protein value of the food after plasma treatment. Change in protein value by the effect of cold plasma is rarely seen after the process. It has been observed that the processing condition and time of the plasma processing has to be considerably high to obtain a change in the protein content of the food product. Cold plasma reduced the amount of immobilized water in the protein-dense myofibril network (Amini, Ghoranneviss, and Abdijadid, 2017).

Carbohydrates are consumed to provide energy to the body. Carbohydrates define the quality of the food products. Cold plasma treatment resulted in reducing all sugar-related compounds, such as glucose and fructose, as well as non-reducible sucrose (Rodríguez et al., 2017). Cold plasma processing of prebiotic orange juice resulted in a decrease in fructose, an increase in sucrose, and oligosaccharide degradation. (Almeida et al., 2015). Although, carbohydrates give us energy, consuming excessive carbohydrates is unhealthy for the human body as compared with that of protein and vitamins. Excessive consumption of carbohydrates could cause obesity. Hence, decreasing the in the content of carbohydrates might be considered advantageous.

5.2. Color

Cold food plasma processing can lead to color changes in food items. This has been experimentally verified by several studies. Changes in food color was because of chemical reactions due to the availability of noble gas and existence of pigments like chlorophyll or anthocyanin (Ramazzina et al., 2015). Color changes in food vary in different situation with cold plasma treatment condition, such as product category, input voltage, time, energy, gas flow input and conditions of storage are some of the key factors color change. A few studies have reported loss of color after a longer treatment time (Lacombe et al., 2015). However, the color of fruit juices are the least affected and can only be observed by trained eyes (Bursać Kovačević, Putnik, et al., 2016; Xu et al., 2017). According to various researchers, CP treatments of strawberries, apples, kiwifruit, cherry tomatoes, cabbage, and carrots resulted in no noticeable color loss. (Misra & Patil, 2014; Niemira and Sites, 2008; Ramazzina et al., 2015). The total color modification after CP treatment of fruit juices was found to be negligible and undetectable with the naked eye (Bursać Kovačević, Putnik, et al., 2016; Xu et al., 2017). These results have shown cold plasma processing has no or minimum effect on the color. The change in food color after treatment should be minimal because if the food appears unattractive, the consumers might not buy it.

5.3. Texture

Texture and color of the food are the most common factors that are noticed at first sight. We cannot compromise the aesthetic value of the food available in the market. Several studies have reported a change in texture of food products after cold plasma processing. We can observe that fruits and vegetables have shown no difference after cold plasma treatment (Misra & Pankaj, 2014; Niemira and Sites, 2008; Tappi et al., 2016). Liquid products also have shown no difference after cold plasma treatment. Increased in texture in high oxygen atmosphere and ozone treatments (Wszelaki and Mitcham, 2000). When DBD is applied to blueberry it shows decrease in firmness, it becomes softer after the treatment (Lacombe et al., 2015; Sarangapani, O'Toole, Cullen, & Bourke, 2017). However, the firmness can be increased in an oxygen rich environment (Misra & Moiseev, 2014). Several studies reported a decrease in crispiness and cooking time (Lee et al., 2016; Sarangapani, O'Toole, et al., 2017; Thirumdas et al., 2016).

5.4. pH value

Several studies have reported that liquid products show a significant reduction in ph. It is observed that products with a high percentage of water are prone to reduction in pH (Lee et al., 2016). Furthermore, DBD treatment of pork loin also reported a reduction in pH (Kim et al., 2013). The association of plasma reactive gases, which create radicals, with moisture found in food products causes the pH to change during plasma operation. Plasma species react with the surface water on solid food products which results in decontamination of the surface only, whereas in liquid products, it reacts and produces radicals with the compound present in the solution. However, numerous studies have reported no change in pH of the food product after plasma treatment (Wan et al., 2017; Xu et al., 2017).

5.5. Acidity

Characteristics of Acidity is not very different from ph. So it is observed that most of the time when there is pH changes acidity also changes. The increases in acidity following plasma treatment are mainly due to the interplay of plasma responsive gases that produce radicals with humidity. Acidity reduction observed in Blueberry by DBD treatment (Sarangapani, O'Toole, et al., 2017). However, it is important to highlight the result of studies related to change in acidity by cold plasma treatment. Sensitivity of Acidity is important for the preservation of the nutritional properties of foodstuffs.

6. Conclusion

Cold plasma has got a huge amount of attention in the food sterilization industry, in recent years. This study has demonstrated that cold plasma can be used to decontaminate surfaces by forming radicals with the components present on the surface. It is clear that cold plasma has no or minimal impact on nutritional quality, pH value, acidity, color, texture. As can be shown, cold plasma is an effective sterilization technique for inactivation of bacteria, viruses, pathogens and other harmful microorganisms. It can tolerate plasma discharges without suffering nutritional damage. However, there are a few studies which have reported a minor change in the food products after plasma processing. Further research can lead to large-scale commercial use of cold plasma sterilization. Cold plasma being an easy, safe, versatile, effective, economical and environmentally friendly method gives a good advantage over commercial decontamination methods. Cold plasma may also be used to eliminate secondary contamination during product packaging. Detailed understanding of cold plasma treatment about the change in food quality should be encouraged, supported and promoted to acknowledge its potential for large-scale decontamination of food products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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